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Preliminary Applications of the Variable Resolution Terrain Model to a Troop Movement Model

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13. ABSTRACT *(Maximum 200 words)*

This report describes a methodology for simulating hastily planned cross-country movement. At the beginning of any military operation, one expects armies to move along routes determined by a thorough analysis of the terrain. However, as the operation progresses, local variations in the terrain may cause some of the troops to deviate from those preplanned routes, sometimes without much time to plan alternate routes. Our model simulates the local variations in troop movement on realistic terrain. The Variable Resolution Terrain (VRT) model was used to supply information about the terrain to the partial differential equation troop movement model. We also added functional overlays to the VRT model to describe environmental features such as bodies of water or foggy regions of the battlefield. By incorporatng this information into our model, the simulated forces can avoid or react to environmental features while executing simple operational orders.

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1. INTRODUCTION

The purpose of this report is to demonstrate that the Variable Resolution Terrain (VRT) model, which was developed by Wald and Patterson (1992) to represent the physical battlefield as a continuously differentiable surface, can be integrated successfully with the reaction diffusion equation (RDE) troop movement model developed by Fields (1993). The resulting VRT/RDE combat simulation model is a versatile simulation tool capable of modeling the movement and interaction of troops on a realistic battlefield. This report discusses the movement of troops; the interaction of the troops will be discussed in a later report. The combined VRT/RDE movement model in this report is presented in three stages. The basic model, presented in the next section, describes cross-country movement of a simulated army on a dry VRT surface. Responses to environmental features, such as water, fog, and smoke are added to the model in the third section. The fourth section of this report discusses some additional responses of the troops to environmental features. Before the combined model is presented, the RDE and the VRT models are described. The reader is referred to the report of Wald and Patterson for details of the VRT model and to the paper of Fields for details of the RDE model.

The primary assumption of the RDE troop movement model is that game pieces on a battlefield tend to move and act as groups rather than as individuals. The behavior of these groups may be described by reaction diffusion equations (RDEs) normally used to describe the movement, spread, and interaction of biological or chemical species. Let $\mathcal{D}$ be a region of $\mathbb{R}^2$ representing the battlefield and B be a homogeneous force of battalion size or larger, which we refer to as the Army B. A general RDE describing the movement of the Army B on the battlefield is given by the following equation:

$$b_t = D_x b_{xx} + D_y b_{yy} + V_x b_x + V_y b_y + I_B. \tag{1}$$

in which b(t,x,y) measures the strength of the army, B at any point (x,y) on the battlefield. Differentiation of the function b is indicated by subscript notation. In this report, the strength of the army at (x,y) will be measured by the number of units (or troops) at that point.

Movement of troops, as modeled by an RDE, has two components: convection and diffusion. The more important of the two, convection, determines the primary direction of troop movement. In many cases, it also determines the speed of that movement, at least to a first order approximation. In Equation 1, the coefficient functions V_x and V_y control the convective movement of the army in the x and y directions, respectively. The second component of movement in the reaction diffusion equation, diffusion, models the natural tendency of substances (or troops) to spread or move randomly. Large diffusion coefficients model scenarios in which the troops spread while traveling. In Equation 1, the coefficient functions D_x and D_y control the diffusion of the army in the x and y directions, respectively. In battlefield simulations, troops are generally lost through attrition and gained through reinforcement. In this simulation, the overall effect of diffusive movement is small, therefore we set the diffusion coefficients D_x and D_y to a small constant value. The last term on the right-hand side, I_B, models the net gain or loss of troops as a function of both space and time. Since the simulations described in this report involve the movement of one army, with no reinforcement or attrition, we neglect I_B.

It is helpful to visualize the vector function (V_x , V_y) as velocity vector field, similar to a magnetic or electric field, which directs the movement of the army on the battlefield. Figure 1 shows a velocity vector field which directs the troops to the black circle in the northeast section of the figure. The vector field is oriented so that the variable x changes in the horizontal direction and the variable y changes in the vertical direction. The figure also shows a contour map of the battlefield with ten equally spaced contours. The heights of some points in the battlefield have been labeled to aid the reader. The length and width of the battlefield are both 10,000 meters. The black circle represents a military objective such as a rendezvous point. The direction of each arrow is a function of terrain characteristics, such as steepness and elevation, and the location of the military objective. Depending on the particular situation being modeled, this field may be static or it may change as a function of time.

The movement of troops or substances on the battlefield is obviously affected by the shape of the battlefield. If information about the terrain can be incorporated into the velocity vector field, (V_x ,V_y), then the vector field will be able to model movement around or over obstacles in the terrain. The "quality" of the terrain information is important. The slope of the terrain at a given point, rather than the altitude of that point, is used to construct the velocity vector field. It is difficult to estimate meaningful slopes from most terrain data bases since information about altitude and slope is given for points that are typically 100 meters apart.

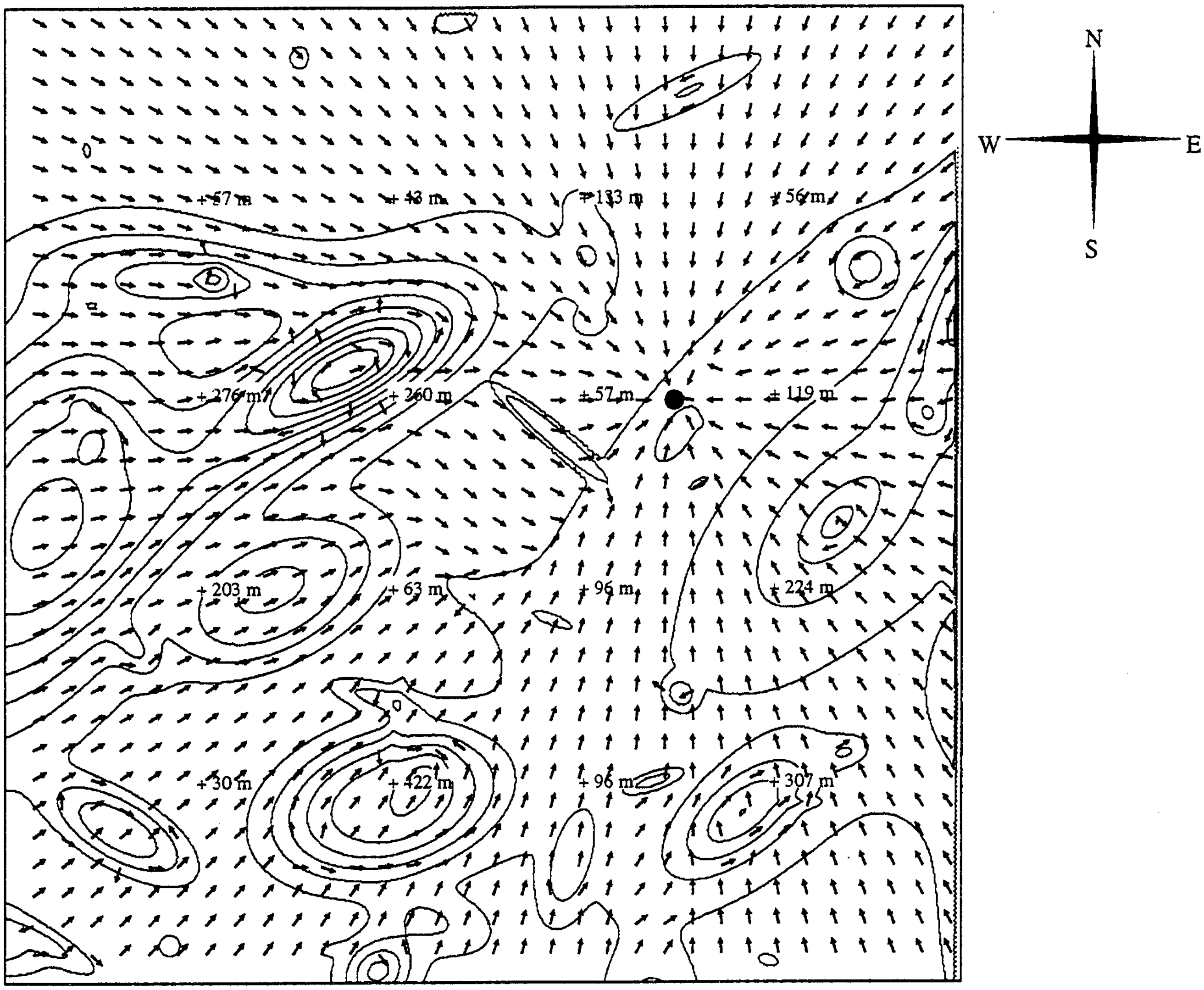

Figure 1. A Velocity Vector Field on a VRT Surface.

We will not use a data base to supply terrain information to our RDE model; instead, we will use the VRT model, which produces a continuous, differentiable surface from building blocks referred to as hills. A general equation for a hill, h(x,y), centered at the point (ξ, η) is written as

$$h(x, y) = \alpha e^{f(\|(x,y), (\xi, \eta)\|_d)}. \tag{2}$$

Here, $\|(x, y), (\xi, \eta)\|_d$ is a metric on $\mathbb{R}^2$. The most familiar metric is the Euclidian distance between points. By varying the metric, the function f, and the parameter α, it is possible to generate hills of any size or shape.

To create a VRT surface, hills of various sizes and shapes are combined together using the principle of *self-similarity.* Self-similar objects are invariant with respect to scale so that a portion of the object, viewed at the proper magnification, resembles the whole object. In our case, the VRT is created from a self-similar distribution of hills. Figure 2, which shows an example of a VRT surface, is a three-dimensional representation of the same battlefield shown as a contour map in Figure 1. For more details of the model, the reader is referred to the paper by Wald and Patterson (1993) and the later papers by Wald (1994).

The VRT model works well with the RDE model since information such as altitude and slope are known for all points on the surface and do not need to be estimated. Furthermore, the terrain can be easily changed to model specific terrain characteristics.

2. CROSS-COUNTRY MOVEMENT

In this section, we model the movement of forces on a VRT surface. For this discussion, all the modeled troops are part of the same homogeneous army, B. The operation used to illustrate the model is a cross-country movement in which the forces have been directed to reach a specified objective on the battlefield. The model is not designed to find "optimal" paths for the forces. Finding optimal paths requires a detailed analysis of the terrain before the operation starts in which routes are specified for the troops as a series of intermediate objective points. The model of troop movement finds "reasonable" paths based on terrain information that may or may not be available before the operation starts.

Let us define the battlefield, $\mathcal{D}$, as a rectangular region of $\mathbb{R}^2$, $\mathcal{D} = \{ (x,y) \mid x_l \leq x \leq x_r \text{ and } y_l \leq y \leq y_r \}$. The function T(x,y), with $(x, y) \in \mathcal{D}$, is the VRT function that describes the surface of the battlefield. The equation which describes the movement of troops on the

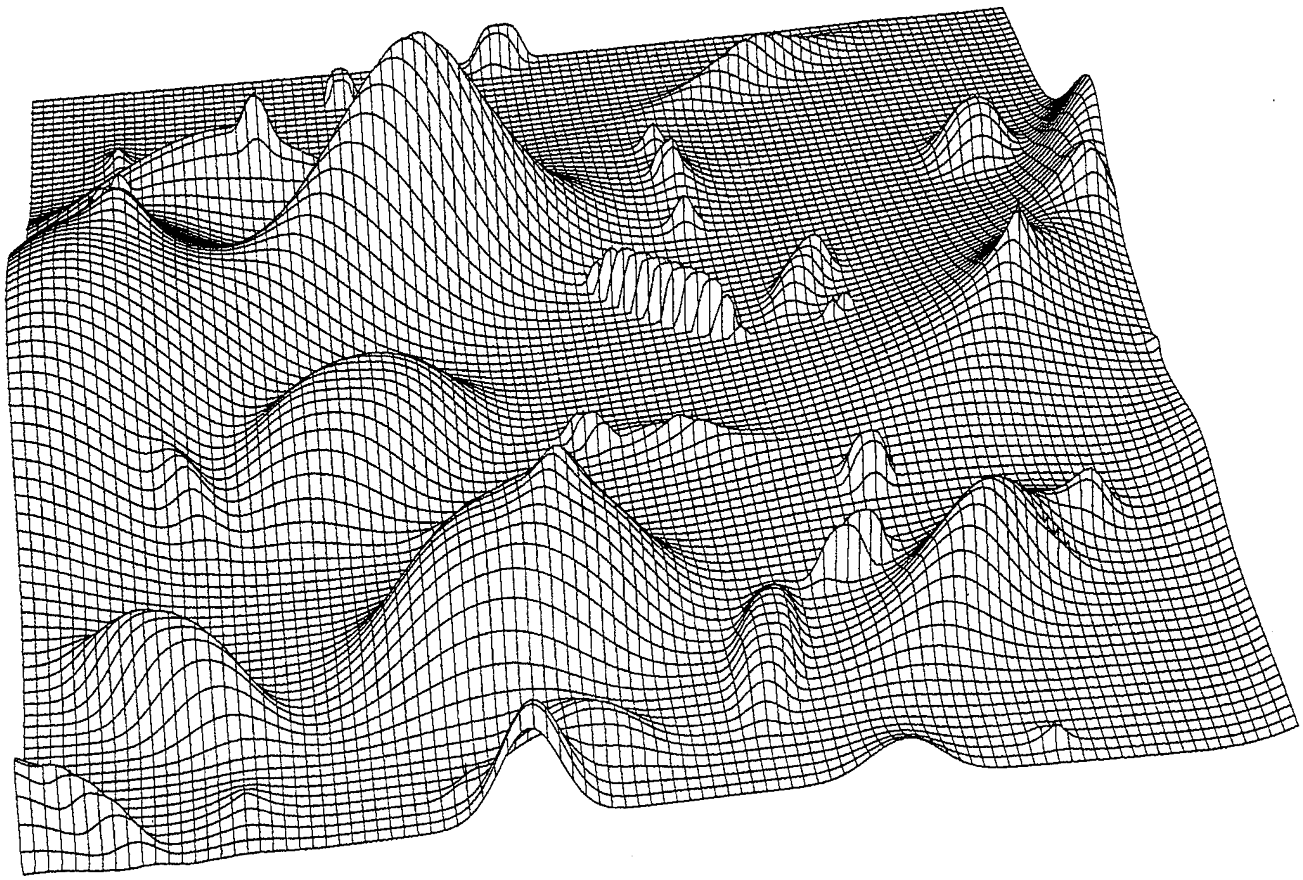

Figure 2. A Three-Dimensional Representation of a VRT Surface.

battlefield, $\mathcal{D}$ is

$$b_t = Db_{xx} + Db_{yy} + V_x b_x + V_y b_y. \tag{3}$$

In Equation 3, b(t,x,y) is the spatial distribution of the the army B at time t; D is the diffusion coefficient; V_x and V_y are convection coefficients. As stated in the introduction, diffusion does not play a major role in troop movement, so for this discussion, we set D to a small positive number. The velocity vector field $(V_x, V_y)^t$ depends on various terrain factors, cross-country movement capabilities of the vehicles and personnel in the unit, and the operational orders for the mission. The next few paragraphs discuss some of these factors separately, before the movement vector field is presented.

We begin with a vector field that implements a simple operational order. Suppose, as an example, the operational order directs the troops to reach an objective point on the battlefield, p = (x_0, y_0). Assuming that terrain does not impede movement, we expect the velocity vector at any point on the battlefield to point directly toward the objective. We also expect the length of the vector (or the speed of the troops) to be nearly the same almost everywhere on the battlefield. The equation for this vector field is given by

$$DG(x, y) = \frac{v}{\varepsilon + \sqrt{(x - x_0)^2 + (y - y_0)^2}} \begin{pmatrix} x - x_0 \\ y - y_0 \end{pmatrix}. \tag{4}$$

The speed of the forces at most points on the battlefield is v units per time length. Obviously, this speed is determined from characteristics of the troops being modeled. Notice that the speed decreases to zero in a circle of radius r(ε), centered at the objective point. The size of the circle can be adjusted to reflect the size of the military objective.

Figure 3 illustrates the vector field defined in Equation 4. The figure also shows a contour map of the VRT battlefield surface T(x,y) with ten equally spaced contours. The height of the battlefield is shown at several points to aid the reader.

Realistic movement on the battlefield requires troops to react to the terrain while moving toward the objective. To incorporate information about the terrain into our movement model, there are two vector valued functions, which are related to the terrain, that are of interest: the orthogonal complement to the terrain gradient, OG, and a steepness gradient, SG. The terrain gradient is TG(x,y) = (T_x , T_y). At any point (x,y), it points in the direction of greatest increase for the function T(x,y). At each point, (x,y), on the battlefield, there are two vectors orthogonal to TG(x,y): $O_1 = (T_y , - T_x)$ and $O_2 = (- T_y , T_x)$. We define OG(x,y) = $\mathcal{C}$ $(- T_y , T_x)$. The

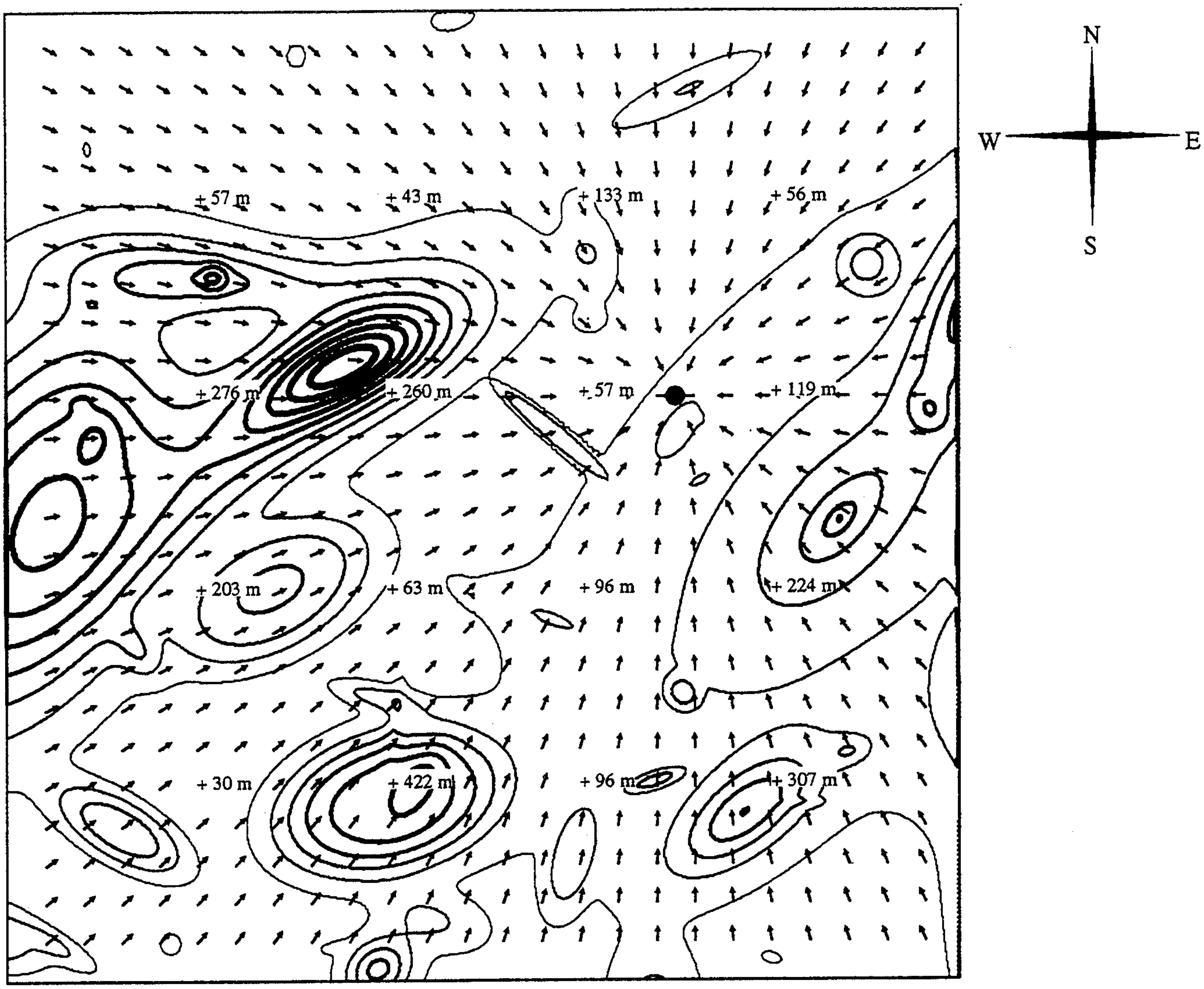

Figure 3. The Destination Vector Field.

term $\mathcal{C}$ is a sigmoid function of the angle between the vectors O_1 and DG defined as

$$\mathcal{C} = \frac{2}{1 + \exp(\alpha \frac{O_1}{\|O_1\|} \cdot \frac{DG}{\|DG\|})} - 1.$$

It controls which of the orthogonal vectors, O_1 or O_2, is used at each point on the battlefield. At any point (x,y), the function OG(x,y) points along the contour containing (x,y). Figure 4 shows the vector field generated by OG(x,y). The vector field has been normalized so that all the vectors have the same length.

To define a steepness gradient, we must first give a measure of the steepness of the terrain. Let the steepness of the terrain at a point (x,y) be defined as

$$\mathcal{S} = \tfrac{1}{2} T_x^2 + \tfrac{1}{2} T_y^2 . \tag{5}$$

Then, the steepness gradient, SG, is the negative of the gradient of the function $\mathcal{S}$,

$$SG(x,y) = -\begin{pmatrix} T_x T_{xx} + T_y T_{yx} \\ T_x T_{xy} + T_y T_{yy} \end{pmatrix}. \tag{6}$$

We classify points on the battlefield as easy, moderate, difficult, or impassable, using the steepness function. The range of steepness values, **S** which is a subset of the set of positive real numbers, can be divided into the following sets:

$$\mathcal{S}_{\text{easy}} = \left\{ s \in \mathbf{S} \mid 0 \le s < s_{\text{easy}} \right\};$$

$$\mathcal{S}_{\text{moderate}} = \left\{ s \in \mathbf{S} \mid s_{\text{easy}} \le s < s_{\text{moderate}} \right\};$$

$$\mathcal{S}_{\text{difficult}} = \left\{ s \in \mathbf{S} \mid s_{\text{moderate}} \le s < s_{\text{difficult}} \right\};$$

$$\mathcal{S}_{\text{impassable}} = \left\{ s \in \mathbf{S} \mid s \ge s_{\text{difficult}} \right\}.$$

The vector field generated by SG(x,y) is shown in Figure 5. The vectors in these fields have been normalized so they are all the same length. The shades of gray on the contour map shown in Figure 5 correspond to the sets given above. White corresponds to the set $\mathcal{S}_{\text{easy}}$, light grey corresponds to $\mathcal{S}_{\text{moderate}}$, medium grey corresponds to $\mathcal{S}_{\text{difficult}}$ and dark grey corresponds to $\mathcal{S}_{\text{impassable}}$.

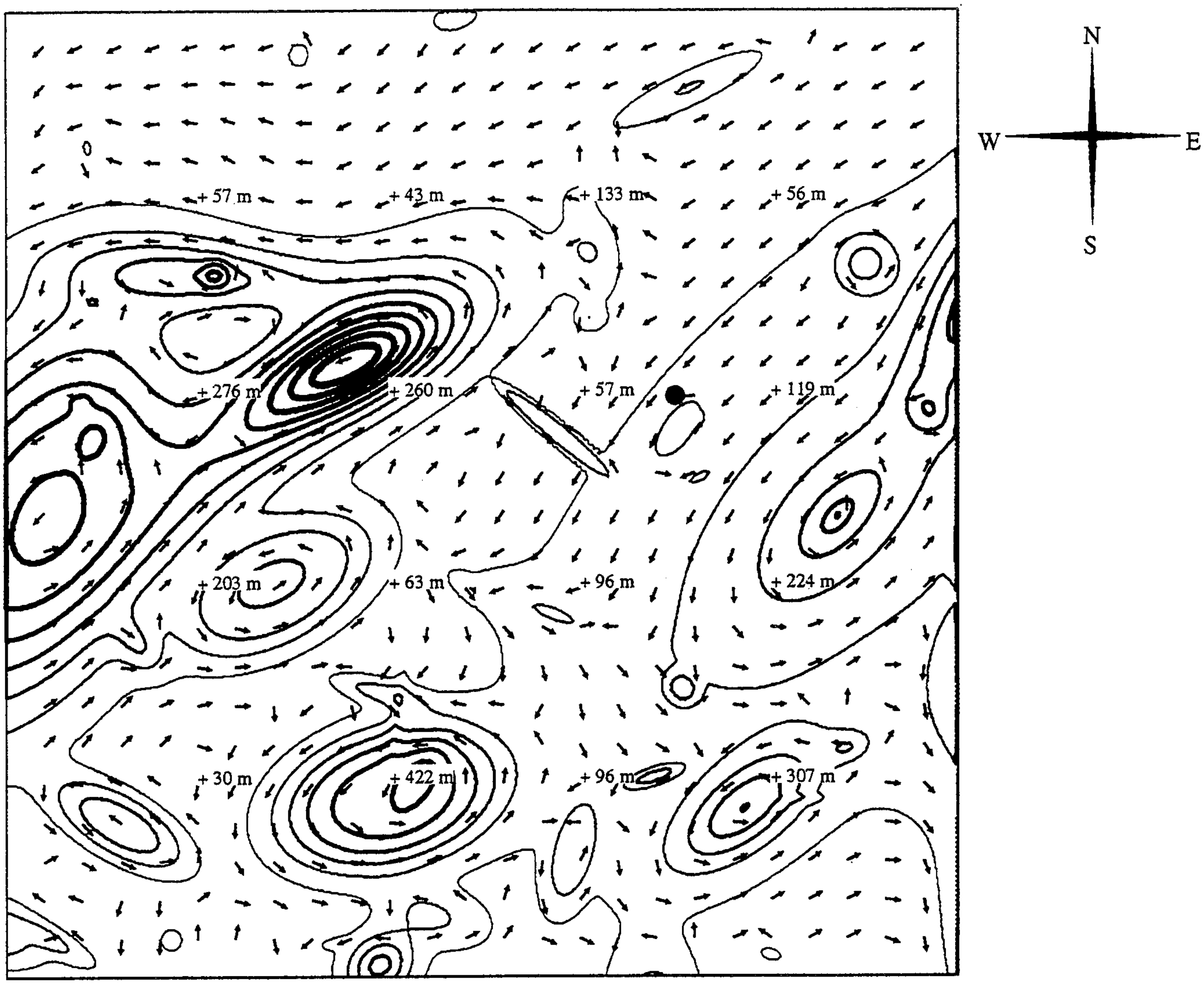

Figure 4. The OG(x,y) Vector Field.

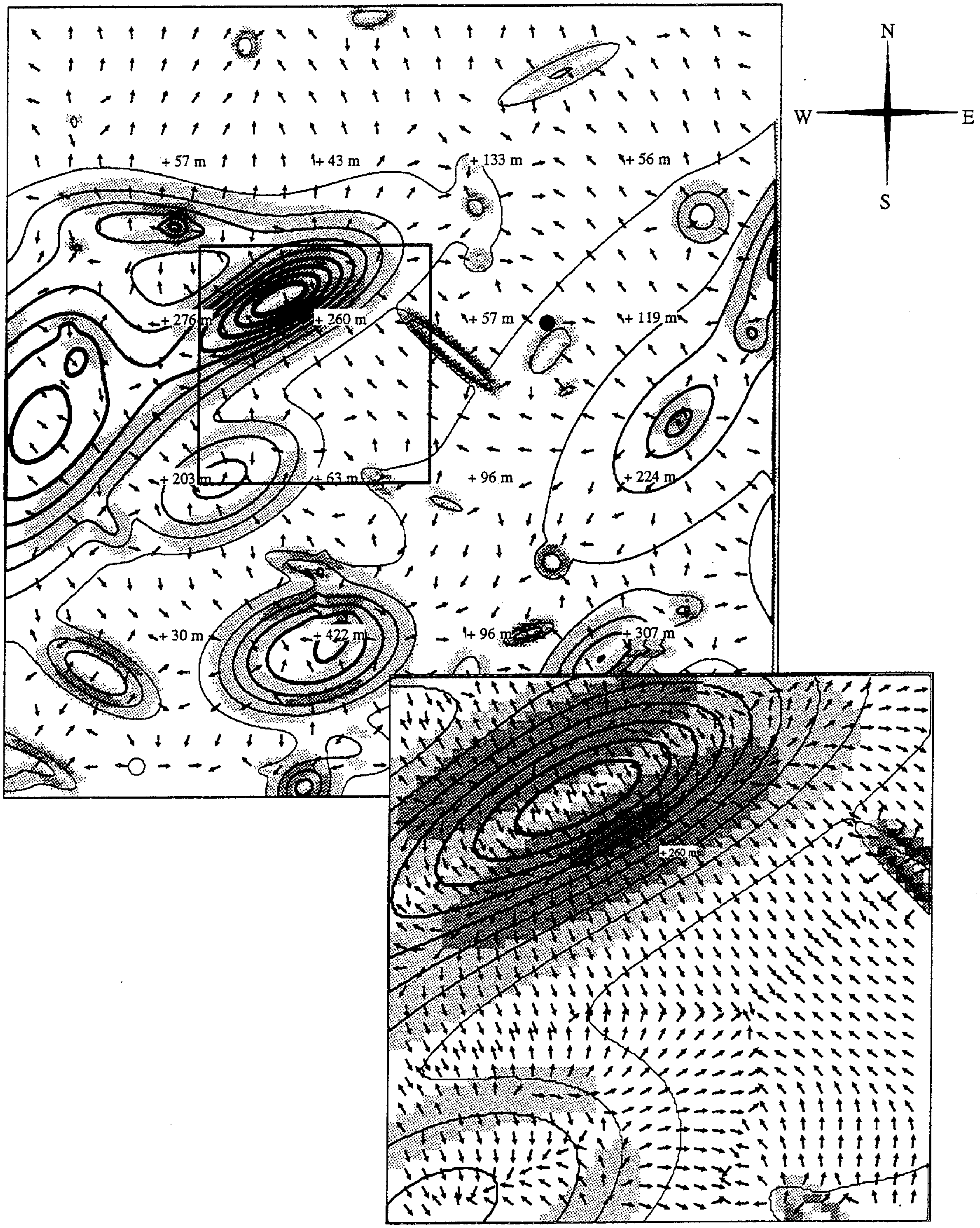

Figure 5. The SG(x,y) Vector Field.

There are two particularly steep regions on the battlefield. One region is the long narrow hill located slightly northeast of the center of the battlefield. Because of the shape of the hill and the sheerness of two of its faces, troops would probably avoid this hill while traveling to the objective. The other steep region, shown both in the main picture and the inset, is located slightly northwest of the center of the battlefield. Notice that this hill is traversable, provided that the troops stay away from its southeastern face.

In our previous work, we used linear combinations of the destination and gradient vector fields to direct the movement of the troops. In this work, we develop a smoother, more accurate, model of troop movement using nonlinear combinations of the destination, gradient and the steepness gradient vector fields to control the movement. The nonlinear weighting functions used in our present model are functions of the steepness of the terrain. In the flatter regions of the battlefield, the terrain does not impede movement, so troops can proceed directly to their destination at full speed along the vector DG(x, y). As the steepness of the terrain increases, units must adjust their direction and speed to either avoid or compensate for obstacles in the terrain. If $s(x,y) \in \mathcal{S}_{\text{moderate}}$, the direction and speed of the troops at the point (x,y) is determined by a combination of DG(x, y) and OG(x, y). Troops at (x,y) with $s(x,y) \in \mathcal{S}_{\text{moderate}}$, proceed primarily in the direction of the destination, while circumventing significant obstacles in the terrain. For points (x,y) with $s(x,y) \in \mathcal{S}_{\text{difficult}}$, troops must leave the area of difficult terrain before proceeding to the objective. For these points, the direction and speed of the troops is determined by a combination of OG(x, y) and SG(x, y). If $s(x,y) \in \mathcal{S}_{\text{impassable}}$, troops are prevented, by the steepness of the terrain combined with the limitations of their equipment, from moving at all.

To implement the troop movement model described in the preceding paragraph, our choices for weighting function fields are bell shaped and sigmoid functions. A sigmoid function has an equation of the form

$$S(s) = \frac{v(s)}{2}\left\{1 \pm \frac{1 - e^{\alpha(s - s_0)}}{1 + e^{\alpha(s - s_0)}}\right\}. \tag{7}$$

It is useful for switching a weight from fully on (or off) to fully off (or on) over a relatively narrow transition range of values centered at s_0. The parameter, α, controls the width of the transition range. The function, v(s), determines the speed as a function of steepness. The bell-shaped curve,

$$N(s) = v(s)e^{-\beta(s - s_0)^2}, \tag{8}$$

is useful for gradually adjusting the weight over a range of values around s_0. The parameter, β, controls the width of the "on" range for the weighting function. Again, the function, v(s), determines the speed as a function of steepness. The weights w_{DG}, w_{OG}, and w_{SG}, are shown in Figure 6. The shading in Figure 6 corresponds to the respective sets. The weight of the destination vector field is nonzero for values in $\mathcal{S}_{easy}$. Both $w_{OG}(x, y)$ and $w_{SG}(x, y)$, as shown in Figure 6, are bell-shaped functions. The weighting function, w_{OG} is centered about a steepness value in the set $\mathcal{S}_{moderate}$; the weighting function w_{SG} is centered about a steepness value in the set $\mathcal{S}_{difficult}$. All the weights are near zero for s(x,y) in the region $\mathcal{S}_{impossible}$.

Figure 7 shows a movement vector field of the form

$$\begin{pmatrix} V_x \\ V_y \end{pmatrix} = w_{DG}DG(x, y) + w_{OG}OG(x, y) + w_{SG}SG(x, y). \tag{9}$$

The destination point is indicated by a black circle in the upper right quadrant of the battlefield. Paths from various points on the battlefield have been added to aid the reader in following the vectors in the field. The steep region, which is northwest of the center of the battlefield, has been enlarged in the inset to show detailed movement in "moderate," "difficult," and "impassable" regions of the battlefield. Notice that troops starting on the northern side of the hill move first down the hill, away from the "difficult" region, then around the hill to the destination. Troops near the top of the hill proceed down the northeast side of the hill in a series of switchback maneuvers.

Not all the paths lead to the destination. Units starting near the southwestern corner of the battlefield are stopped by the impassable hill before they can reach their destination. Since the vector field given in Equation 9 uses only local information to determine the direction of each vector, the units do not "see" the impassable hill until they are stopped by it. Using information from a region surrounding each point on the battlefield will allow the units to change direction to avoid obstacles, such as the narrow hill northeast of the center of the battlefield shown in Figure 7.

To accomplish this improvement, we replace DG, in Equation 9, which currently points to the objective point, with a more general term. For each point (x,y) on the battlefield, let R(x,y) be a region surrounding that point. We replace the vector DG with the following vector:

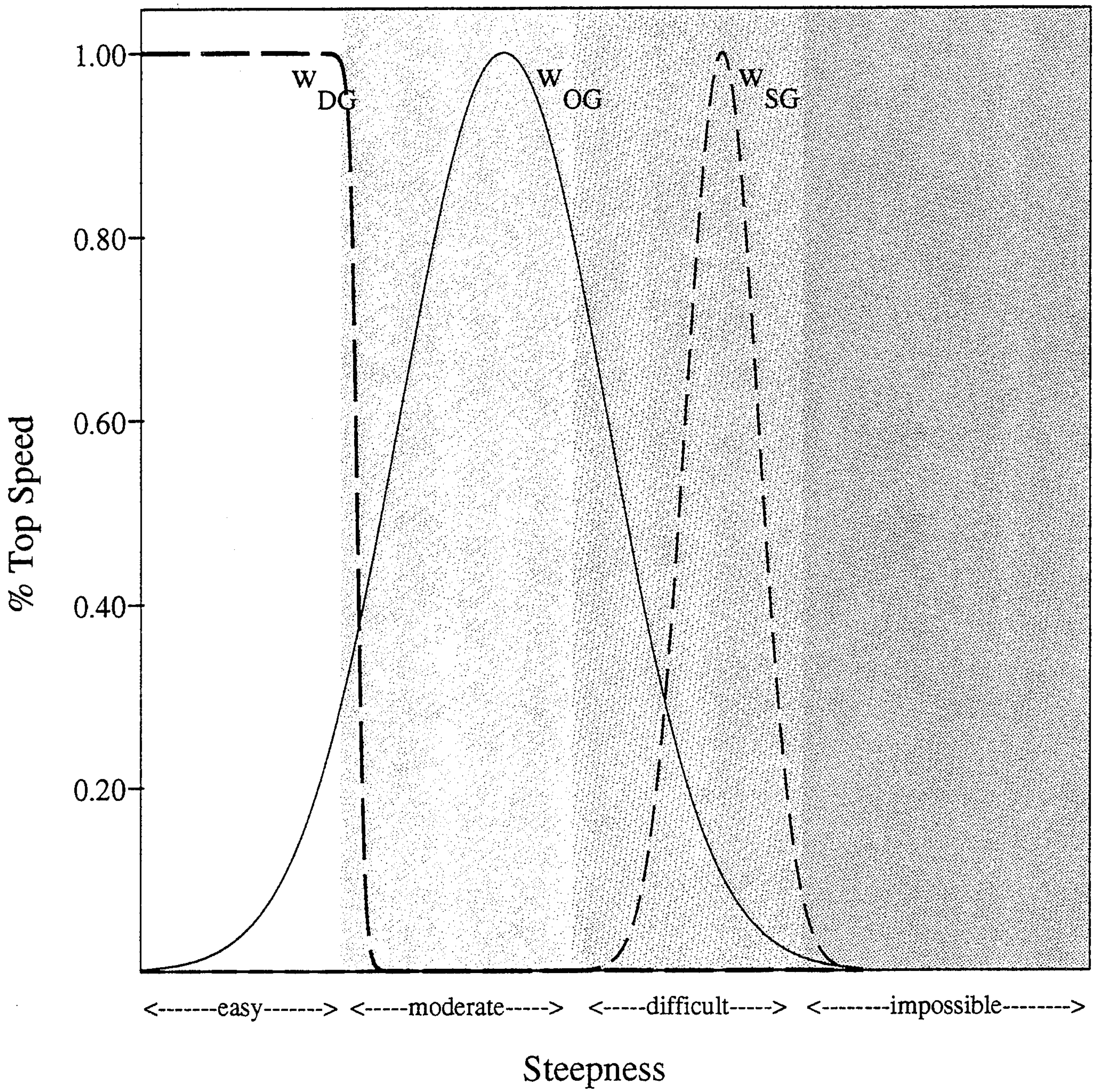

Figure 6. The Weighting Functions.

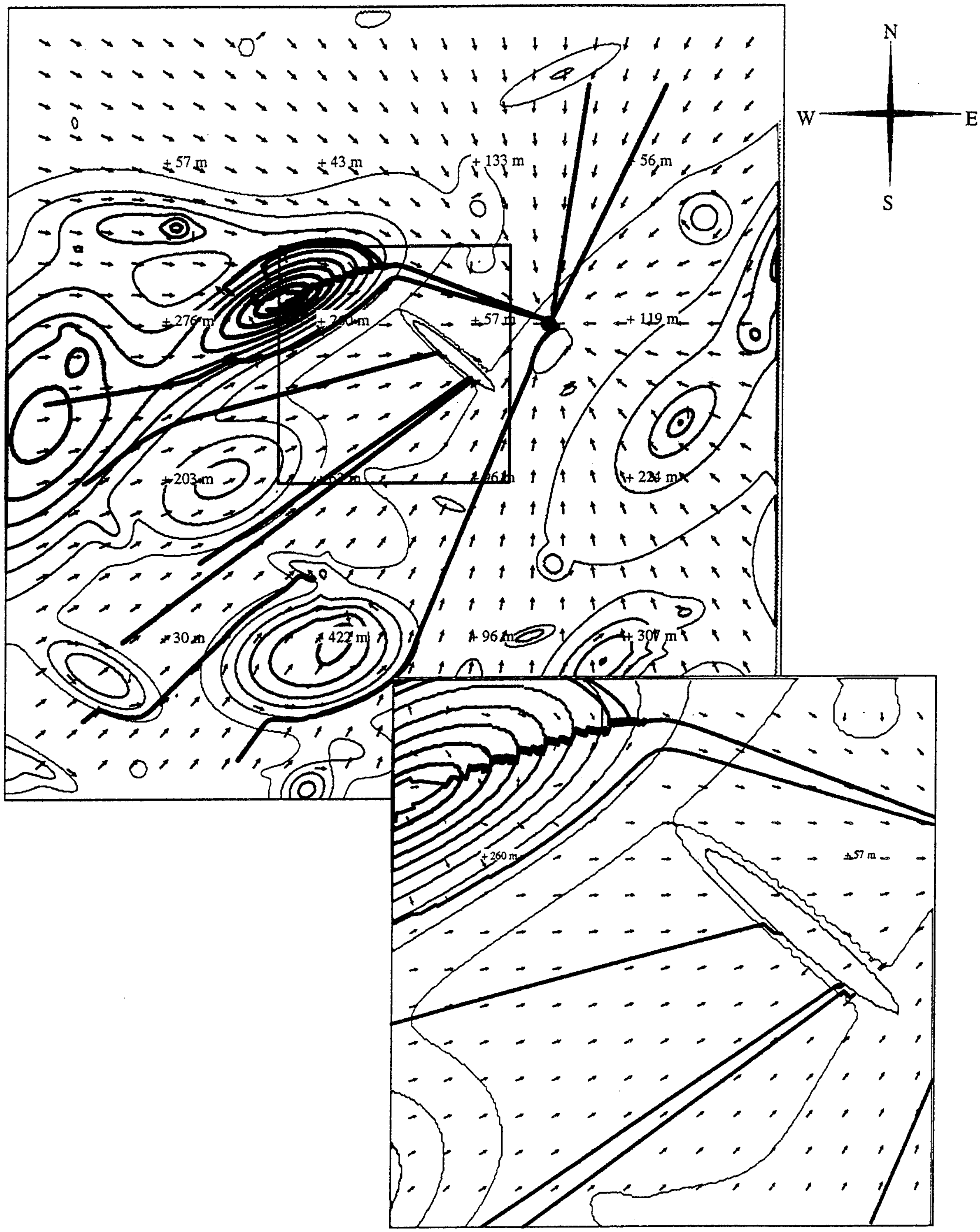

Figure 7. The Movement Vector Field.

$$\tilde{DG} = \frac{\int\int_{R(x,y)} w_1(\mathcal{S}(r,s))OG(r,s) + (1 - w_1(\mathcal{S}(r,s)))DG \, drds}{\int\int_{R(x,y)} drds} \tag{10}$$

The function w_1 determines how strongly steep sections of R(x,y) influence the movement at (x,y). Figure 8 shows the improved vector field which uses $\tilde{DG}$. In this case, w_1 is a sigmoid function of the form

$$w_1(\mathcal{S}) = \frac{1 - \exp^{\alpha(\mathcal{S}-\mathcal{S}_c)}}{1 + \exp^{\alpha(\mathcal{S}-\mathcal{S}_c)}} \tag{11}$$

Notice that the troops in the southwest corner of the battlefield "see" the hill and go around it. Movement in other regions of the battlefield is basically unaffected. By changing w_1 and R(x,y), it is possible to model other behaviors.

3. AVOIDING WATER

The previous section presented a model of troop movement on dry land. This section discusses an extension of the model that allows the troops to move realistically on battlefields with regions of the terrain covered by water, fog or contaminants. It is beyond the scope of this report to discuss the models that add features such as water, fog, or contaminants to the battlefield. Instead, we use these models to place features on the terrain and confine our discussion to the movement of troops in response to these features. This section focuses on the movement of the troops in response to water on the battlefield.

In the discussion that follows, T(x,y), with $(x,y) \in \mathcal{D}$, is a VRT function that describes the surface of the battlefield. W(x,y), with $(x,y) \in \mathcal{D}$, is a function that describes the distribution of water over the VRT battlefield. In this model, the surface of the battlefield is assumed to be impermeable so that the water forms a layer of varying thickness on top of the surface of the battlefield; W(x,y) is the depth of the water layer at (x,y). Since the underlying terrain surface is continuously differentiable, we assume that the water surface is a continuous, non-negative valued function so that at least one derivative exists at each point. Figure 9 shows a distribution of water on the battlefield surface. For clarity, it is the same surface we used to illustrate the discussion in the previous section. The shading in the figure indicates the depth of the water at each point on the battlefield. The water depth has been divided into four

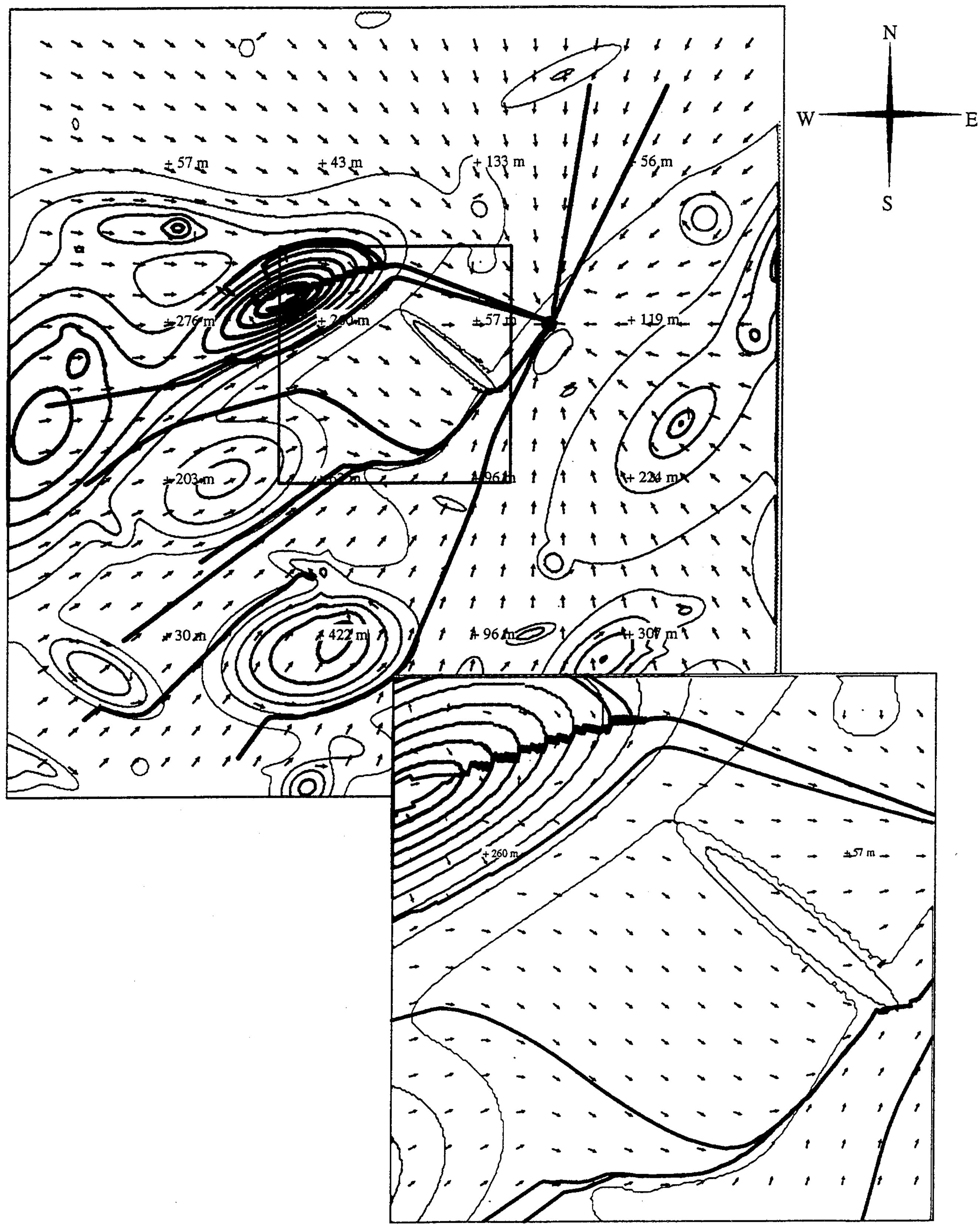

Figure 8. The Improved Movement Vector Field.

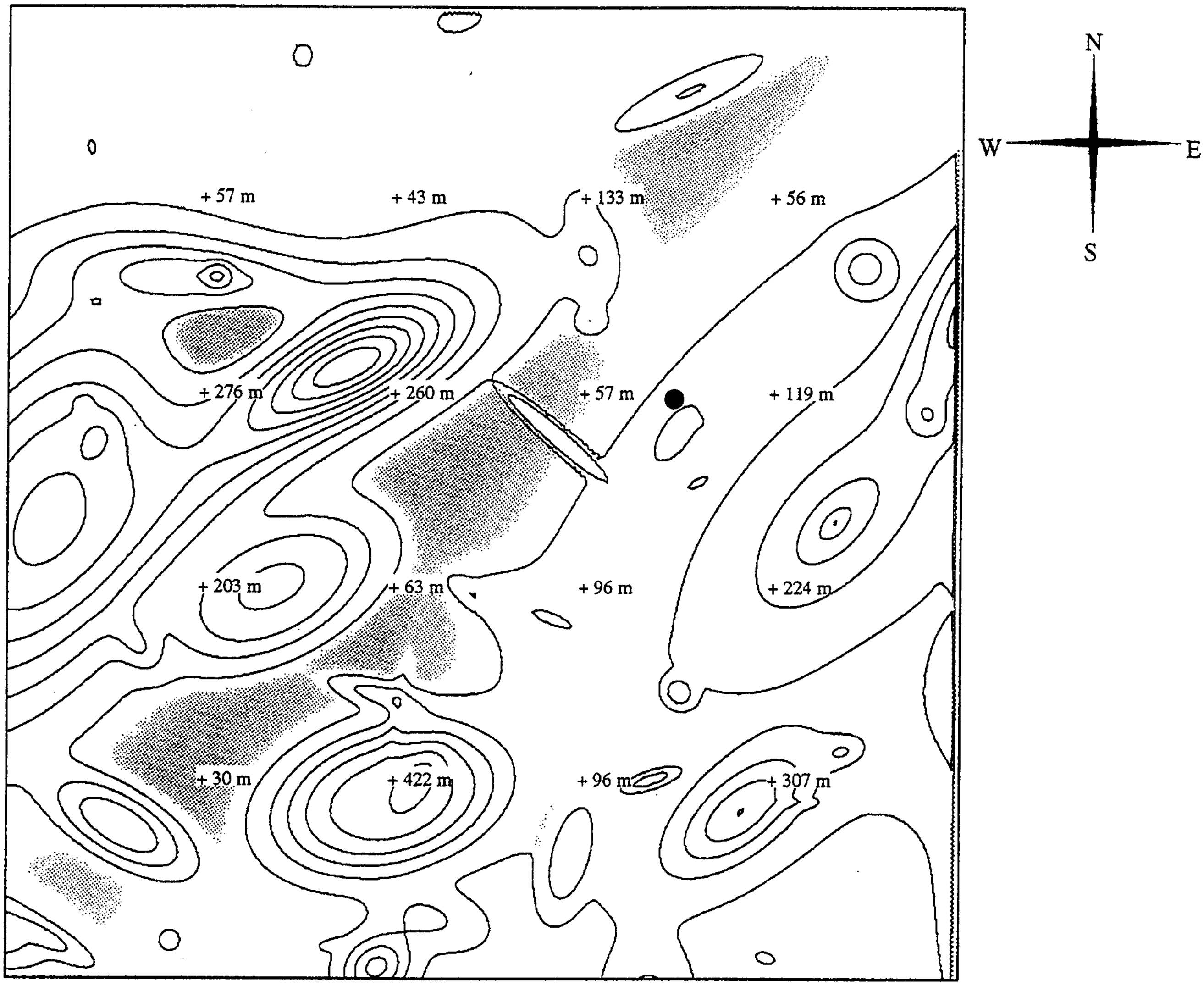

Figure 9. A VRT Surface with Water Features.

classifications: Dry, which is shaded white; Low-Shallow, which is shaded light gray; High-Shallow, which is shaded medium grey; and Deep, which is shaded dark gray.

We assume that the troops or vehicles do not "swim" so that movement is restricted to dry or shallow regions of the battlefield. In the "drier" regions of the battlefield, the effect of water on troop movement is negligible, and movement is controlled primarily by the terrain and destination vectors discussed in the previous section. As the depth of the water increases, its effect on troop movement becomes more pronounced. The two vectors associated with the water surface, $WG = (W_x, W_y)^t$, the gradient of the water surface, and $WOG = (-W_y, W_x)^t$, the vector orthogonal to WG, are used to direct the troops around and away from water.

A vector field that describes the movement of troops on a "wet" battlefield is given by the equation

$$\begin{pmatrix} V_x \\ V_y \end{pmatrix} = w_{OG}(w, s)OG + w_{SG}(w, s)SG + w_{DG}(w, s)DG + w_{WG}(w)WG + w_{WOG}(w)WOG. \quad (12)$$

The vector fields generated by DG, OG, and SG were discussed in the previous section. The weights for these "dry-land" vectors still depend on the steepness of the terrain. In this field, however, the depth of the water, w, at each point on the battlefield is a major factor in determining the weight of each vector in the vector field equation.

Figure 10 shows the weights as functions of the water depth, w, for a fixed value of terrain steepness, s. The water depth has been divided into four classifications: Dry, Low-Shallow, High-Shallow and Deep. For points on the battlefield classified as "Dry," water is not a factor so w_{WG} and w_{WOG} are near zero while w_{DG}, w_{OG}, and w_{SG} are close to their maximum values. For points classified as "Low Shallow," the vector WOG dominates the vector field which inhibits movement toward deeper water. At "High Shallow" points on the battlefield, the troops need to move away from deep water; consequently, WG dominates the vector field. Obviously, troops at points on the battlefield classified as "Deep" cannot move.

Figure 11 shows the vector field and some paths superimposed on the contour map of the "wet" battlefield. The inset shows a more detailed picture of the vector field in a wet area of the battlefield. The vectors in the deep water areas have length zero since troops cannot move in these areas. In the shallow regions, three distinct types of movement can be seen in the vector field: movement away from the deep water, movement along a water contour, and "dry land" movement.

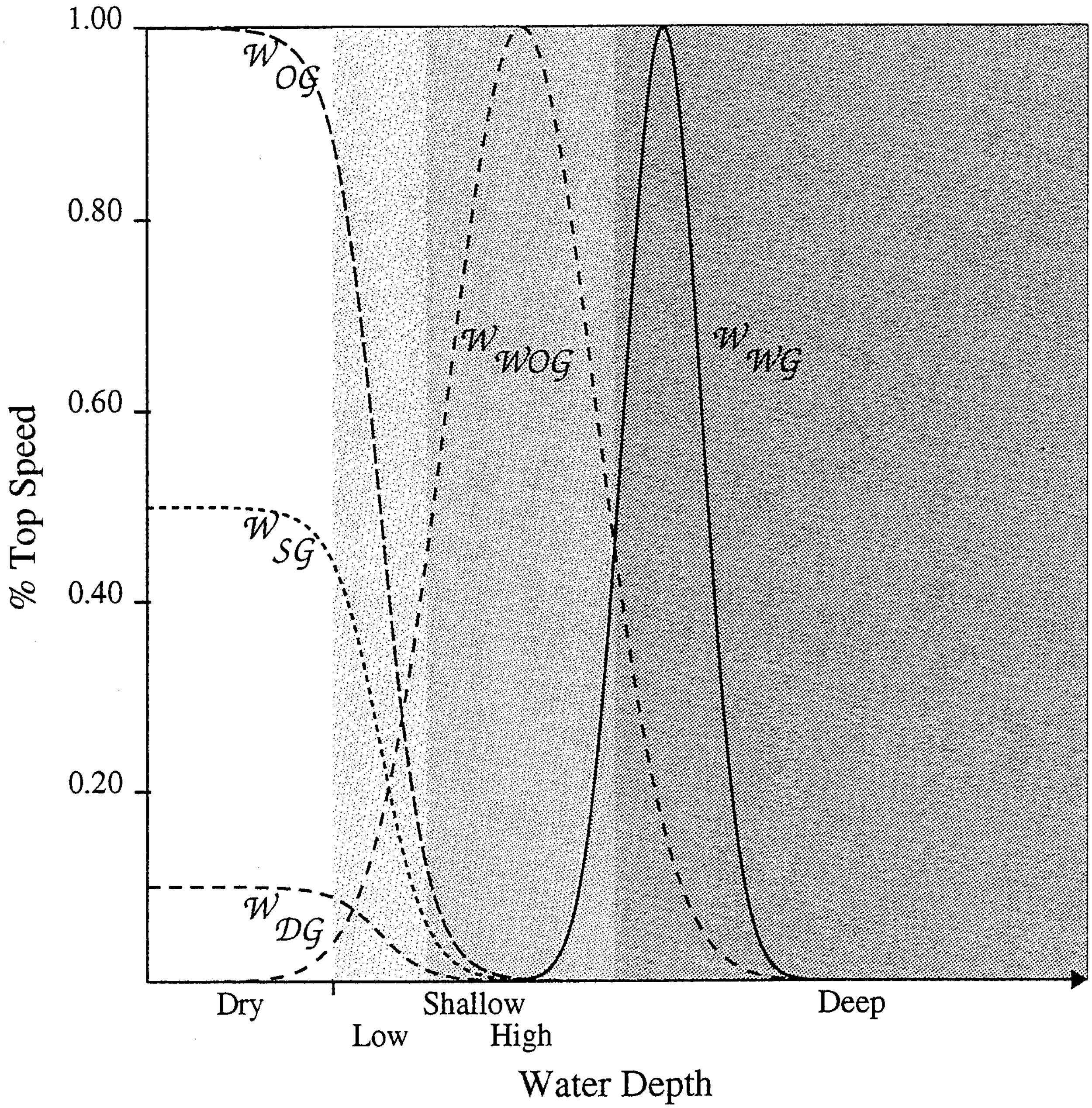

Figure 10. The Weighting Functions.

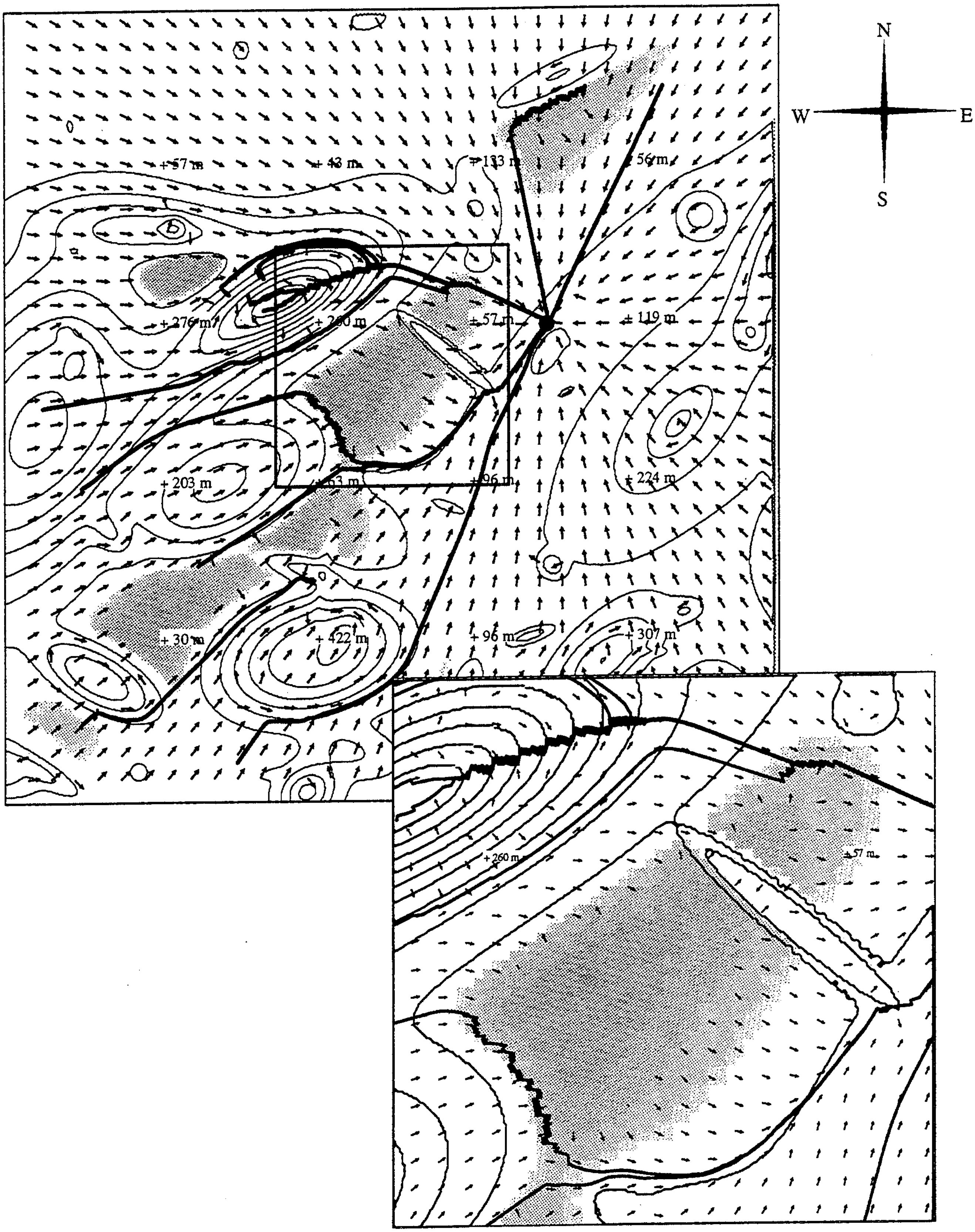

Figure 11. The Wet Vector Field.

4. MODELING DEGRADED PERFORMANCE

Environmental factors such as fog or smoke also affect troop movement. By reducing the ability of the troops to see, these factors degrade the performance of the troops. The troops may slow down or possibly make mistakes. This section looks at ways to measure the effects of environmental factors on the movement of the troops on the battlefield. We use the example of a foggy battlefield to illustrate this section, but similar techniques could be used to degrade the performance level of troops due to other environmental hazards such as chemical contamination.

Let T(x,y), with $(x, y) \in \mathcal{D}$, be a VRT function that describes the surface of the battlefield. F(x,y), with $(x, y) \in \mathcal{D}$, is a function that describes the density or thickness of the fog at each point on the battlefield. Figure 12 shows a "foggy" battlefield. In the figure, the grey shading indicates the thickness of the fog. The darkest grey corresponds to the thickest fog.

To slow the troops down in the foggy regions, suppose that the speed of the troops depends on the thickness of the fog, f. A sigmoid function such as

$$v(f) = \frac{v}{2}\left\{1 + \frac{1 - e^{\alpha(f - f_0)}}{1 + e^{\alpha(f - f_0)}}.\right\} \tag{13}$$

in which v is the speed of the troops in clear conditions, f_0 is the density of fog at which the speed of the troops is reduced by 50%, and α is a positive constant that controls how fast the speed decreases.

We can measure the effect that fog has on the amount of time required to complete a mission. Suppose that troops must reach the objective point given by the black circle in Figure 12. Some examples of such paths are shown in Figure 12. Let P(x,y) be a path followed by the unit. In clear conditions, the time, t_c, to reach the objective is described by the line integral:

$$t_c = \int_P \frac{1}{v(x, y)} \, dP \tag{14}$$

in which v(x,y) is the speed at each point along the path P. The amount of time, t_f, required to move along the path, in foggy conditions, is given by the line integral

$$t_f = \int_P \frac{1}{v(f, x, y)} \, dP \tag{15}$$

in which v(f,x,y) is given by Equation 13. If the units on path P are too sensitive (as determined by the size of the parameter α) to foggy conditions, they may never reach their destination. The

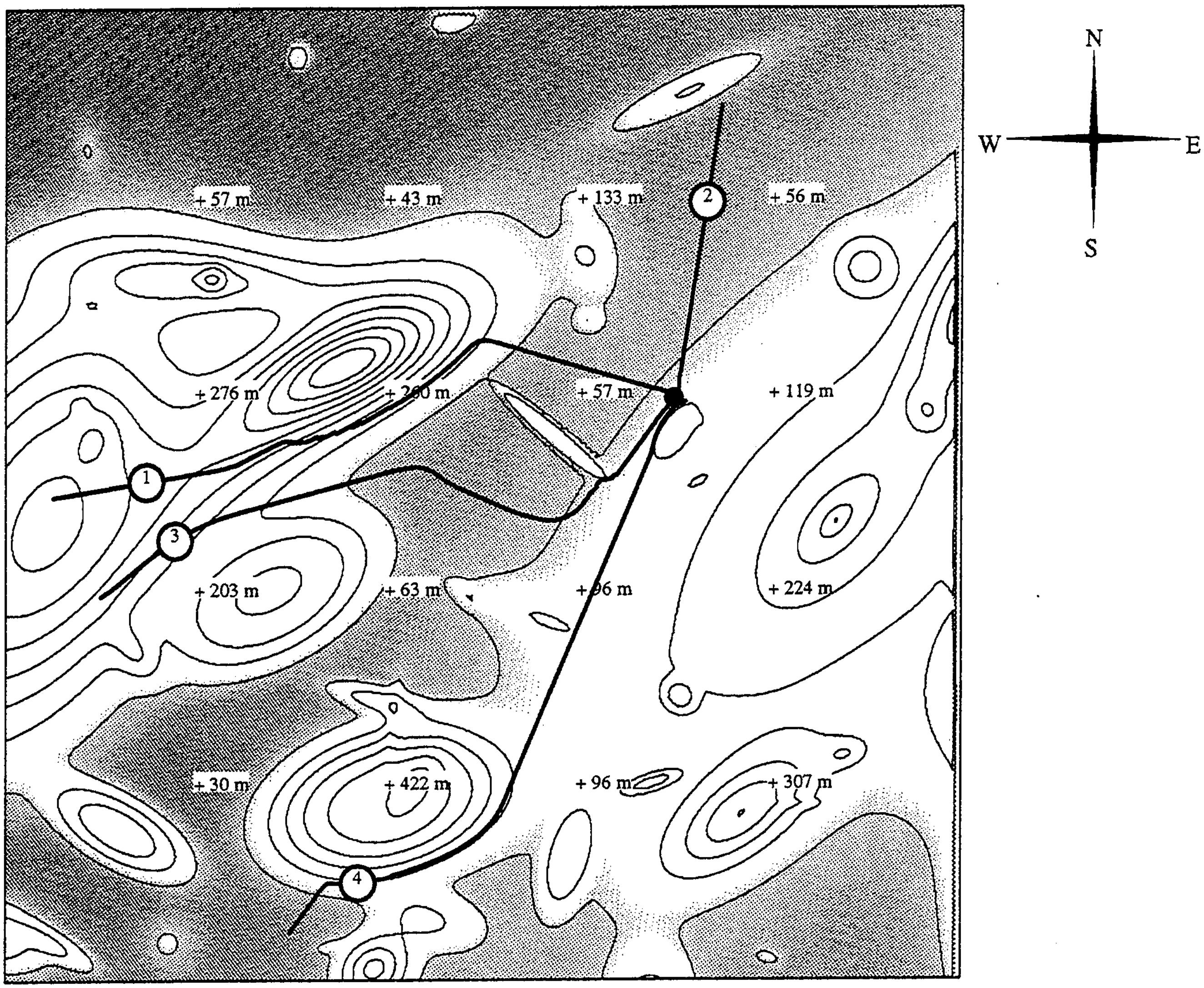

Figure 12. Four Paths on a Foggy Battlefield.

ratio, t_f/t_c shows how fog affects the time required to complete the mission, provided the units follow the same path to the objective in both clear and foggy conditions. For the paths shown, the time to complete the mission increased by 25% for Path #1, 7% for Path #2, 50% for Path #3, and 1% for Path #4. Of course, the increase in the time required to complete the mission depends on the velocity of the unit at each point along the path and on the parameters α and f_0 in Equation 13.

In the previous section, we used information from a region, R(x,y), around each point on the battlefield to construct a vector field that allowed the troops to "see" and avoid obstacles in the terrain. We can incorporate reduced visibility due to fog and other environmental factors into our movement model by making the size of the region R(x,y) a function of the density of the fog. Figure 13 shows three paths that start and end at the same point. Notice that all these paths circumvent the hill in the northeast quadrant of the battlefield. Each path has a different sensitivity to the fog density; consequently, the units on these paths "see" the hill at different times.

5. SUMMARY

In this report, we have developed a model of troop movement that combines the VRT methodology for representing terrain as a continuous, differentiable surface with the RDE methodology which models the movement of troops and substances such as water, fog, or contaminants over the surface of the battlefield. By incorporating information from the VRT model into the velocity coefficient functions, we are able to model complex troop movement. For instance, while following operational orders that dictate the overall direction of movement, troops using "local" information (information at a point) respond appropriately to the terrain by avoiding steep regions of the battlefield. Depending on the nature of the terrain, units that start near each other may take very different paths to reach an objective. This "responsive" behavior is modeled by the velocity coefficient function. No additional logic needs to be added to the model. By incorporating "regional" information, the model provides the troops the ability to see and avoid steep hills in the distance.

Environmental factors such as water, fog, smoke, or contamination are modeled as "functional overlays" on the basic VRT surface. These functions can also be incorporated into the velocity coefficients of the RDE model so that troops avoid regions of the terrain covered by

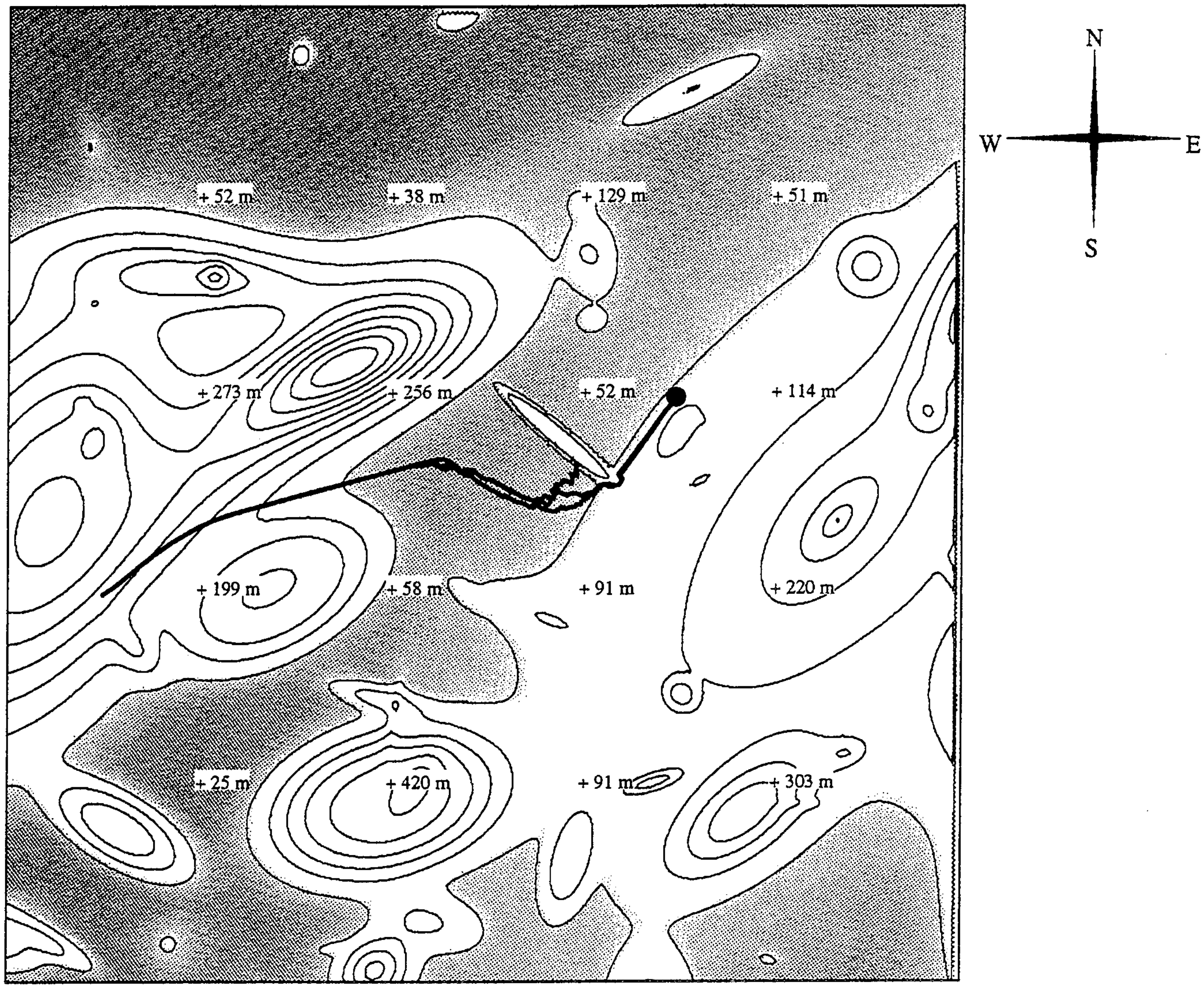

Figure 13. Altering Visibility as a Function of Fog Density.

water, fog, or contamination.

In the future, we intend to further refine our troop movement model by incorporating our previously developed models of "responsive" troop movement (Fields, 1993). The "responsive" movement models allow troops to respond dynamically to both opposing and friendly forces on the battlefield. Combining the "responsive" movement models with the current work will result in a model that can automatically model the movements and interactions of opposing forces on a realistic battlefield.

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